Revision of the southern distribution limit for the tropical marine herbivore *Syphonota geographica* (A. Adams & Reeve, 1850) (Heterobranchia: Aplysiidae) in a global climate change hot-spot

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ABSTRACT

The aplysiid sea hare, *Syphonota geographica* has a predominantly circumtropical distribution. Over the last 15 years, it has spread throughout the eastern Mediterranean Sea where it is regarded as an alien, Lessepsian migrant. Observations from southern Europe and the Middle East illustrate the capacity of *S. geographica* to invade and establish populations in novel locations. Whilst historic records from the Australian east coast indicate a latitudinal distribution from northern Queensland south to Sydney, observations reported in this paper confirm that its range extends to the southern east coast, an area regarded as an important climate change hot-spot. These records not only represent an important southward shift in range, but are also the most southerly global observations for this tropical taxon. Observations from the Mediterranean and those reported here, were generated by citizen scientists, highlighting the substantial benefit of public engagement in ongoing programs that document, and monitor changes in, marine biodiversity.

Key words: climate change, East Australian Current, Sea Slug Census, Anaspidea, sea-hare, citizen science, New South Wales.

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Introduction

The Aplysiidae is a small family, containing 11 genera, of predominantly herbivorous molluscs, all of which are characterised by the presence of distinctive cephalic tentacles (rhinophores) that resemble the ears of a rabbit – hence the common name 'sea hare' (Nimbs *et al*. 2017). Animals in the monospecific genus *Syphonota* H. & A. Adams, 1854 are morphologically distinct from the other aplysiids, wherein their rhinophores, set close together, arise between the anterior end of the parapodial flaps (Bebbington 1974). The sea hare *Syphonota geographica* (A. Adams & Reeve, 1850) was first described based on a specimen found off the northern coast of Java during the scientific survey of the H. M. S. *Samarang* in 1843–1846 (Adams & Reeve, 1850). The species has several synonyms which are listed in Nimbs *et al*. (2017). It has a predominantly tropical distribution across the Indo-West Pacific and Atlantic (Caribbean) (Rudman 1999) with a recent migration into the Mediterranean Sea (Yokes and Rudman 2004).

A distinctive set of lines and spots that together form a map-like pattern give *S. geographica* its specific name (Bebbington 1974; Rudman 2003) (Figure 1A). Interestingly, the name *Aplysia scripta* was given to this taxon by Bergh (1905) with reference to the body pattern which was thought to resemble Arabic script (Rudman 1999). This is certainly characteristic of some tropical Indo-Pacific specimens, however, patterns on animals from cooler waters more closely resemble cartographic markings (Figs. 1B & 1C).

Whilst many sea slugs are cryptic and often diminutive, the sea hares are readily identified, at least to genus (Willan 1979; Willan 1998; Nimbs 2017), and although its body pattern can be variable, *S. geographica* is rarely confused with its confamilials (pers. obs.). Nevertheless, there are considerable differences in the body pattern between tropical and temperate specimens. In other sea slug taxa, even minor variations in pattern or colour can be used to visually delineate species (Gosliner *et al.* 2015). This, and a broad, tropical distribution indicate the possibility that *S. geographica* may represent a species complex. As with other aplysiids, many older taxonomic descriptions are uncritical or vague, and thus several phenotypes require reexamination using molecular and morphological analyses to determine their true identity (Nimbs *et al*. 2017).

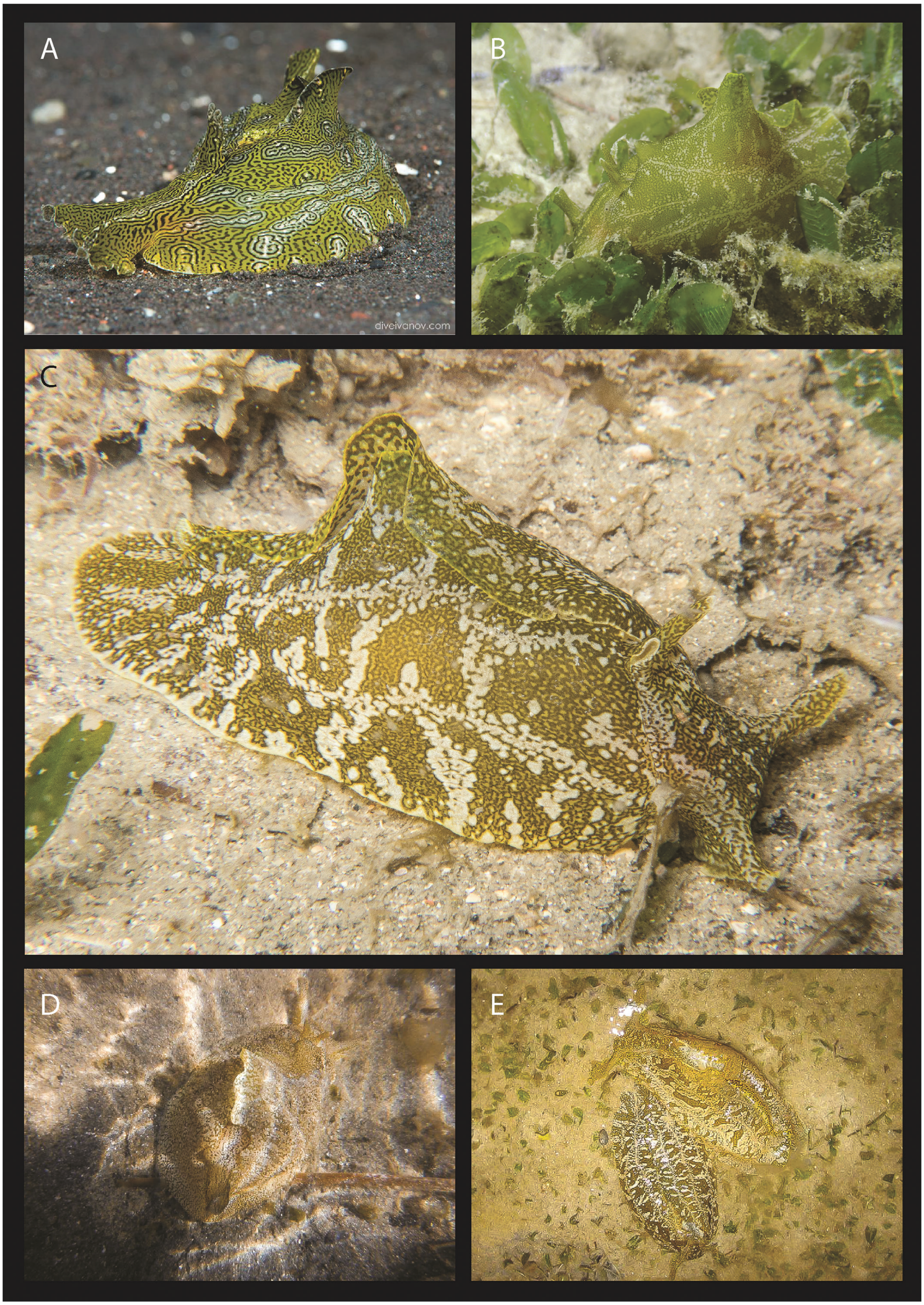

Fig. 1: (A) *Syphonota geographica* from Bali, Indonesia, exhibiting the highly ornate body pattern characteristic of tropical specimens. Photo: Yury Ivanov, Tulamben, Bali, Indonesia, 18 December 2015; (B) A specimen exhibiting a subtropical body pattern, amongst the seagrass *Halophila ovalis* (R.Brown) J.D.Hooker, 1858. Photo: Matt Nimbs, Gold Coast Seaway, QLD, night-time, 2 metres, *Sea Slug Census* 30 September 2016; (C) A warm-temperate specimen from Port Stephens, NSW. Photo: Stephen D. A. Smith, night-time, 4 metres, Nelson Bay *Sea Slug Census,* 14 September, 2015; (D) A temperate specimen from Merimbula Lake, NSW, Australia. Photo: Liz Allen, 14 March, 2017; (E) First observation from Merimbula Lake, NSW, Australia. Photo: Lyn Scrymgeour, 22 February, 2007.

Most aplysiids consume marine algae, cyanobacteria or algal films (Thompson 1976; Yonow 2008), however *S. geographica* is a specialised consumer of sea grass, specifically plants in the genus *Halophila* Du Petit-Thouars, 1806 (Carbone *et al.* 2008; Gavagnin *et al.* 2005). Animals are nocturnally active, remaining buried in sediments during the day, often adjacent to their food (Rudman 1999; MN pers. obs.). They are capable of swimming by flapping their parapodia (Rudman 1999).

In the Mediterranean Sea, both *S. geographica* and its host sea grass, *Halophila stipulacea* (Forsskål) Ascherson, 1867, are regarded as invasive, alien marine species (Gavagnin *et al.* 2005; Zenetos *et al.* 2005). Some authors believe that *S. geographica* is a Lessepsian migrant that entered the Mediterranean Sea via the Suez Canal (Gavagnin *et al.* 2005), later establishing self-perpetuating populations (Zenetos *et al.* 2005) in Italy in 1999 (Karachle *et al.* 2016), Turkey in 2002 (Yokes and Rudman 2004), Greece in 2002 (Mollo *et al.* 2008) and Lebanon in 2003 (Crocetta *et al.* 2013).

South-eastern Australia is a recognised climate change hot-spot (Hobday and Lough 2011) where, under the influence of warming sea water and strengthening of the southward-flowing East Australian Current (EAC), locally acclimated species are likely to contract southward and be replaced by tropical species (Beger *et al.* 2014; Przeslawski *et al.* 2008). With long-lived, planktonic larvae (Kempf 1981), sea hares are well suited to capitalise on opportunities to expand their range in the presence of warming conditions if receiving sites support suitable resources (habitat and food) (Nimbs *et al.* 2017). This is particulary the case in eastern Australia where the EAC is predicted to strengthen and provide a more consistent supply of tropical larvae to locations at higher latitudes (Malcolm *et al.* 2011; Smith 2011; Beger *et al.* 2014).

In response to earlier reports of range extensions for several east Australian sea slug species, we recently documented the diversity of the sea hares, highlighting the importance of central New South Wales (NSW) as a global diversity hot-spot. Moreover, we recognised the need to publish comtemporary distribution data of sea slugs in NSW to establish a baseline for the detection of future shifts in distribution among this group (Nimbs and Smith, 2017; Nimbs *et al.* 2017).

The purpose of this paper is therefore to document observations of *S. geographica* in southern NSW. These represent an important southward shift in range for a highly distinctive tropical sea hare in a well-known region of ocean warming.

Materials and Methods

The observations summarised in this paper were made during the inaugural Sapphire Coast Sea Slug Census program in April, 2017. The Sea Slug Census program is a citizen science project developed by Southern Cross University and citizen scientists from central NSW (Smith and Davis 2013) that, through specific census events, engages with volunteers to document sea slug diversity at specific locations. Since its inception in December 2013, the program has been expanded to other locations in NSW and Queensland (QLD). In addition to running specific events, the program encourages ongoing image sharing and discussion, facilitating capacity building and the development of identification skills amongst volunteers. Several important records have already been generated and published (Nimbs and Smith 2016; Nimbs *et al.* 2016; Nimbs *et al.* 2015) and the data have also contributed to a comprehensive overview of the distribution of sea slugs in NSW (Nimbs and Smith 2017). Much of the data generated by volunteers has also been used to develop materials to further build the capacity of participants to find and identify a range of sea slugs (Nimbs 2017).

Participants are primarily engaged through social media (*Facebook*) which allows the upload of photos for identification and discussion by other users (Sea Slug Census 2015; Sapphire Coast Sea Slug Census 2017). Metadata are included for each image, including location and date. The establishment of a hub for photographic submission and discussion not only provides sharing of recent discoveries, but can also encourage broader investigation into the historical presence of species. On a number of occasions, including for *S. geographica* as reported here, this has led to important new information on historical distributions.

Comparison with published distribution sources and regional lists enables ready detection of species in novel locations. Global distribution data were sourced from the literature and online sources (Table 1) and mapped to illustrate the global distribution of *S. geographica.* These data include location (latitude and longitude) and date of observation.

Results and Discussion

Historic and contemporary records for *Syphonota geographica* indicate a circumtropical distribution (Rudman 1999). However, as with most sea slug taxa, records tend to be from well-worked but discrete locations (Gosliner and Draheim 1996), which is manifest as apparent patchiness in summary maps of distribution. *Syphonota geographica* has a widespread distribution across the western Pacific extending to New Caledonia, south eastern Australia and north to Japan. In the Indian Ocean it has been recorded from southern Western Australia, India (including the Andaman Islands) and southern Africa and, in the Atlantic, from the Caribbean and Mediterranean Seas (Fig. 2, Table 1).

On the east Australian coast, the majority of *S. geographica* observations are from QLD (Table 1). It has been recorded from three locations in NSW: Nelson Bay

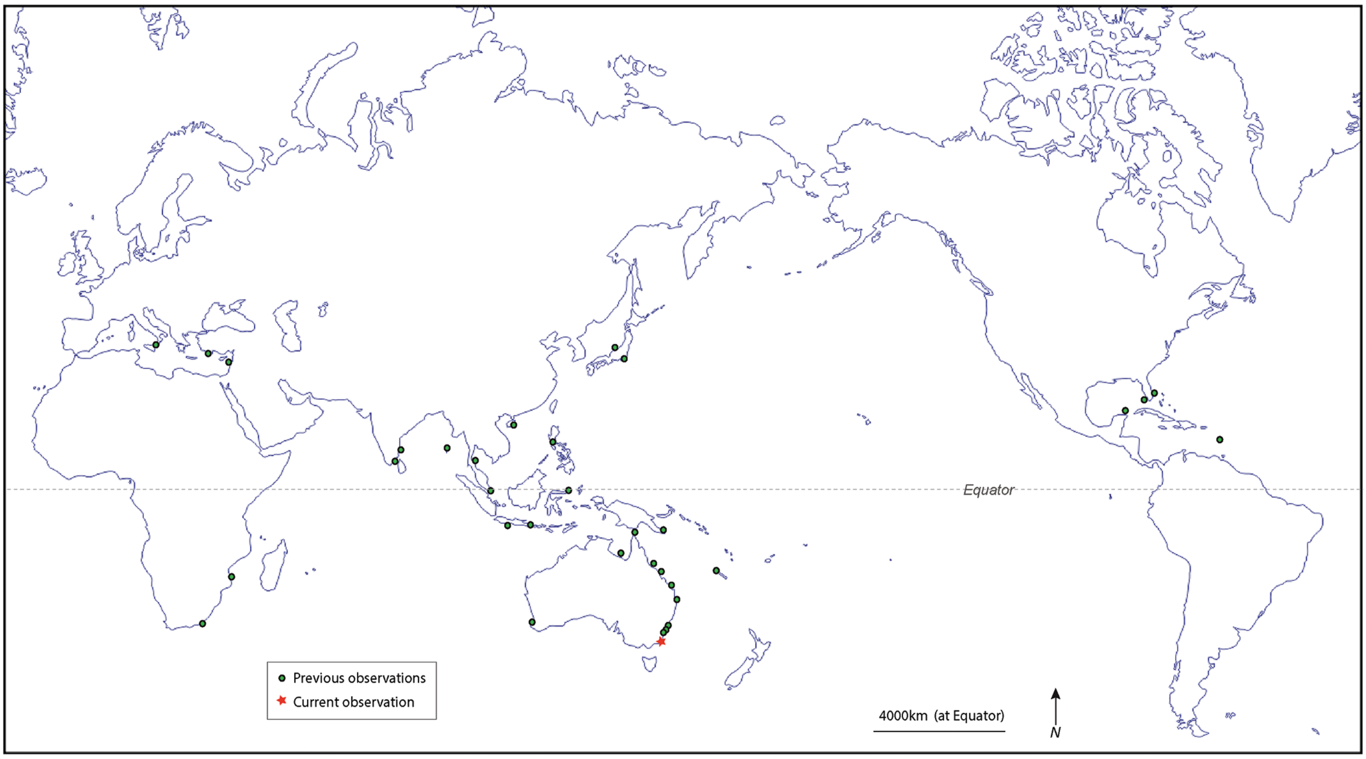

Fig. 2. Global distribution of *Syphonota geographica* from historic and contemporary records. Its southernmost observation at Merimbula Lake, NSW, Australia is marked with a red star.

(Rudman 1999; pers. obs.), Terrigal (Hunt 2011) and Sydney (Rudman 2000), with the latter being the most southerly distribution in Australian waters.

On 14 March 2017, a single specimen of *S. geographica* was observed in the shallow waters of Merimbula Lake near Stanley Park, at Merimbula, NSW, Australia (36°53'17"S 149°54'59"E. Datum: WGS84). The animal was photographed in the field by Elizabeth Allan and then posted to the Facebook page *Sapphire Coast Sea Slug Census* for identification (Sapphire Coast Sea Slug Census 2017). Although the characterisitc body pattern is comparatively indistinct, the animal was identified as *S. geographica* based on the presence of small, closely-set rhinophores that arise between the anterior ends of the parapodial flaps (Fig. 3). Reduced colour intensity, body pattern and a general contraction in length is characteristic of senescence in some sea slugs (Nimbs and Smith 2014). Also, as a nocturnally active species, *S. geographica* is more likely to be observed at night. It is therefore possible that this specimen was moribund (Fig. 1D), explaining both the pale colouration and its presence on the surface during the day.

At the time, this record was thought to be the first observation of this species at this location (Merimbula) which represented a considerable range extension. However, *Facebook*-based discussions led to the posting of an image of two specimens (taken by Lyn Scrymgeour) in 2007, 10 years prior to the 2017 *Sea Slug Census*, from the same location. In this observation, two specimens were observed at low tide on sandy sediments amongst patches of sea grass (Fig. 1E), at Merimbula Lake near Stanley Park, Merimbula, NSW, Australia on 22nd February 2007.

Such events highlight the importance of maintaining good records, close interaction between the citizen scientist and the research community, the need for accessible identification tools [such as NudiKey (Nimbs 2017)] and continued surveys of regional sea slug diversity. Indeed, some of the first observations of *S. geographica* in the Meditteranean were made by well-informed citizen scientists (Karachle *et al*. 2016). Observations at Merimbula extend its southern range by an additional 330 km. On the extensive Australian east coast, such a distance may appear insignificant: however, this observation is particularly important for two reasons. Firstly, it represents a shift into a new Integrated Marine and Coastal Regionalisation of Australia benthic meso-scale bioregion, the Twofold Shelf (Commonwealth of Australia 2006), a temperate zone which is biologically distinct from the Hawkesbury region surrounding Sydney. Secondly, while the species is present on the south-western Australian coast (NudiPixel 2008), and South Africa (Gilchrist 1900), these observations represent the most southerly observation for this species globally (Fig. 2; Table 1).

In some cases, reports of range shifts for rarely observed taxa may be reasonably atttributed to sampling effort or as an artefact of detectability (Bates *et al*. 2015). On the east coast, the diversity of areas close to populations centres are relatively well known, however data for some sections of the NSW coast is lacking

Table 1. Global distribution records of *Syphonota geographica.* Datum: WGS84

Location	Record Coordinates	Year	Reference
Asia			
Java Sea	06°25'53''S 111°22'10''E	1843 - 1846	Adams and Reeve (1850)
Lembeh, Indonesia	01°27'02''N 125°13'20''E	2009	Rudman (1999)
Bali, Indonesia	08°09'32''S 114°58'43''E	2006	Rudman (1999)
Changi, Singapore	01°18'35''N 104°00'28''E	2003	Rudman (1999)
Anilao, Philippines	13°45'27''N 120°54'56''E	2014	Ballesteros et al. (2017)
Gulf of Thailand	12°39'53''N 100°48'45''E	1895	Bebbington (1974)
Toyama Bay, Japan	36°45'59''N 137°10'50''E	1952	Bebbington (1977)
Sagami Bay, Japan	35°16'53''N 139°32'56''E	1955	Baba (1955)
Hainan, China	19°59'55''N 104°49'33''E	1965	Bebbington (1977)
Pulicat Lake, India	13°33'33''N 80°12'35''E	2015	Sethi et al. (2015)
Thoothukundi, India	08°45'42''N 78°12'81''E	n.d.	OBIS (2016)
Andaman Islands, India	12°24'39''S 93°00'23''E	1944	Bebbington (1974)
Oceania (not Australia)			
Koumac, New Caledonia	20°35'05''S 164°16'01''E	1993	Rudman (1999)
Milne Bay, Papua New Guinea	10°04'12''S 150°07'56''E	2008	Coleman (2008)
Africa			
Pomene, Mozambique	22°54'17''S 35°32'56''E	2008	Rudman (1999)
East London, South Africa	33°01'34''S 27°55'13''E	1900	Gilchrist (1900)
Durban, South Africa	29°52'35''S 31°03'01''E	1906	Bebbington (1974)
Americas			
Dominica	15°24'58''N 61°26'54''W	2004	Rudman (1999)
Guadeloupe	16°17'03''N 61°35'26''W	2012	Ortea et al.(2012)
Cancun, Mexico	21°36'04''N 87°32'12''W	n.d.	OBIS (2016)
Dry Tortugas, Florida, USA	24°37'40''N 82°52'30''W	n.d.	OBIS (2016)
Palm Beach, Florida, USA	26°48'12''N 80°02'18''W	2010	Frank (2010)
Europe & western Asia			
Lebanon	33°55'18''N 35°33'04''E	2013	Crocetta et al. (2013)
Fethiye, Turkey	36°38'9''N 29°06'58''E	2004	Yokes and Rudman (2004)
Porto Germeno, Greece	38°09'13''N 23°13'24''E	2005	Gavagnin et al. (2005)
Messina, Sicily, Italy	38°11'59''N 15°33'57''E	2005	Scuderi and Russo (2005)
Australia			
Thursday Island, QLD	10°34'24''S 142°12'53''E	1895	Bebbington (1977)
Mornington Island, QLD	16°32'11''S 139°33'22''E	1990	ALA (2015)
Magnetic Island, QLD	19°10'20''S 146°49'22''E	2004	Klussmann-Kolb (2004)
Sarina Beach, QLD	21°23'43''S 149°18'58''E	1963	ALA (2015)
Togoom , QLD	25°14'44''S 152°39'59''E	1961	ALA (2015)
Moreton Bay, QLD	27°23'59''S 153°09'20''E	1952	ALA (2015)
Nelson Bay, NSW	32°43'03''S 152°08'27''E	2015	Nimbs et al. (2017)
Terrigal, NSW	33°26'28''S 151°26'24''E	2011	Hunt (2011)
Sydney, NSW	33°50'22''S 151°15'21''E	2015	Nimbs and Smith (2017)
Fremantle, WA	32°3'31''S 115°44'28''E	2007	Nudi Pixel (2008)
Merimbula, NSW	36°53'17''S 149°54'59''E	2007, 2017	This paper

and thus diversity in these regions may be greater than currently recognised. Recent consolidation of historic and contemporary records has established a distribution baseline (Nimbs and Smith 2017) which permits recognition of observations in novel locations. Regardless of causality (detectability or sampling effort), documenting range extensions is imperative in a region of rapid environmental change (Nimbs and Smith 2016; Nimbs *et al.* 2016; 2015). Observations in Merimbula Lake are unlikely to be an artefact of effort. The relative size and distinctness of *S. geographica*, here found in a readily accessible habitat where marine biodiversity surveys have been conducted previously (M. McMaster pers. comm.), means that oversight prior to 2007 is unlikely. This 10-year gap between observations may also be symptomatic of the high temporal variability recored for many sea slug populations over a range of scales (Angulo-Campillo 2005; Nybakken 1978; Smith and Nimbs 2017).

The relatively recent establishment of populations in the Meditteranean Sea illustrate the capacity of *S. geographica* to migrate and establish populations at novel locations (Zenetos *et al.* 2005) in temperate latitudes. Whilst not regarded as an invasive species in Australia, its presence in temperate waters well south of its previously documented range in a climate change hot–spot is clearly important. With the roll-out of the *Sea Slug Census* program into temperate and cool-temperate regions in southern Australia, areas which are highly susceptible to warming, it is likely that the frequency of observations of warm temperate and tropical species will continue to increase. However, given the limited data on the outcome of novel species interactions among sea slugs, the consequences of these range-shifts remain unclear (Bates *et al.* 2014).

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